VIRGINIA TECH TRANSPORTATION INSTITUTE

Developing an Eco-Cooperative Automated Control System (Eco-CAC)

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2019 DOE Vehicle Technologies Office Annual Merit Review
June 13, 2019 – Arlington, VA

Project ID: eems028

Overview

Timeline

- ❑ Start date: 10/1/2017
- ❑ End date: 6/30/2020
- ❑ Percent complete: 40%

Budget

- ❑ **Total project funding:**
  - DOE share: $1,507,197
  - VTTI share: $83,588
- ❑ **Funding for FY 2017:**
  - DOE share: $752,291
  - VTTI share: $84,480
- ❑ **Funding for FY 2018:**
  - DOE share: $754,906
  - VTTI share: $168,068

Project Goals/Barriers

- ❑ Improve energy efficiency of ICEVs, BEVs, PHEVs, and HEVs by integrating multiple connected and automated vehicle (CAV) applications
- ❑ Computational difficulty of accurately modeling and simulating large-scale transportation systems
- ❑ Uncertainty in measuring the energy impact of CAVs in large-scale transportation networks

Collaborators (Not funded by Project)

- ❑ Morgan State University (MSU)
- ❑ VW America, Electronics Research Laboratory
- ❑ TTS, Inc.
- ❑ VDOT

Relevance/Objectives

CAVs are significant emerging technologies that are expected to result in transformative improvements to the transportation system. The main project objective is to substantially reduce vehicle fuel/energy consumption by integrating vehicle control strategies with CAV applications for an affordable, efficient, safe, and accessible transportation future. The project will develop a novel integrated control system that

(1) routes vehicles in a fuel/energy-efficient manner and balances the flow of traffic entering congested regions,

(2) selects vehicle speeds based on anticipated traffic network evolution to avoid or delay the breakdown of a sub-region,

(3) minimizes local fluctuations in vehicle speeds (also known as speed volatility) on freeways and arterials, and

(4) enhances the fuel/energy efficiency of various types of vehicles while focusing on ICEVs, BEVs, HEVs, and PHEVs.

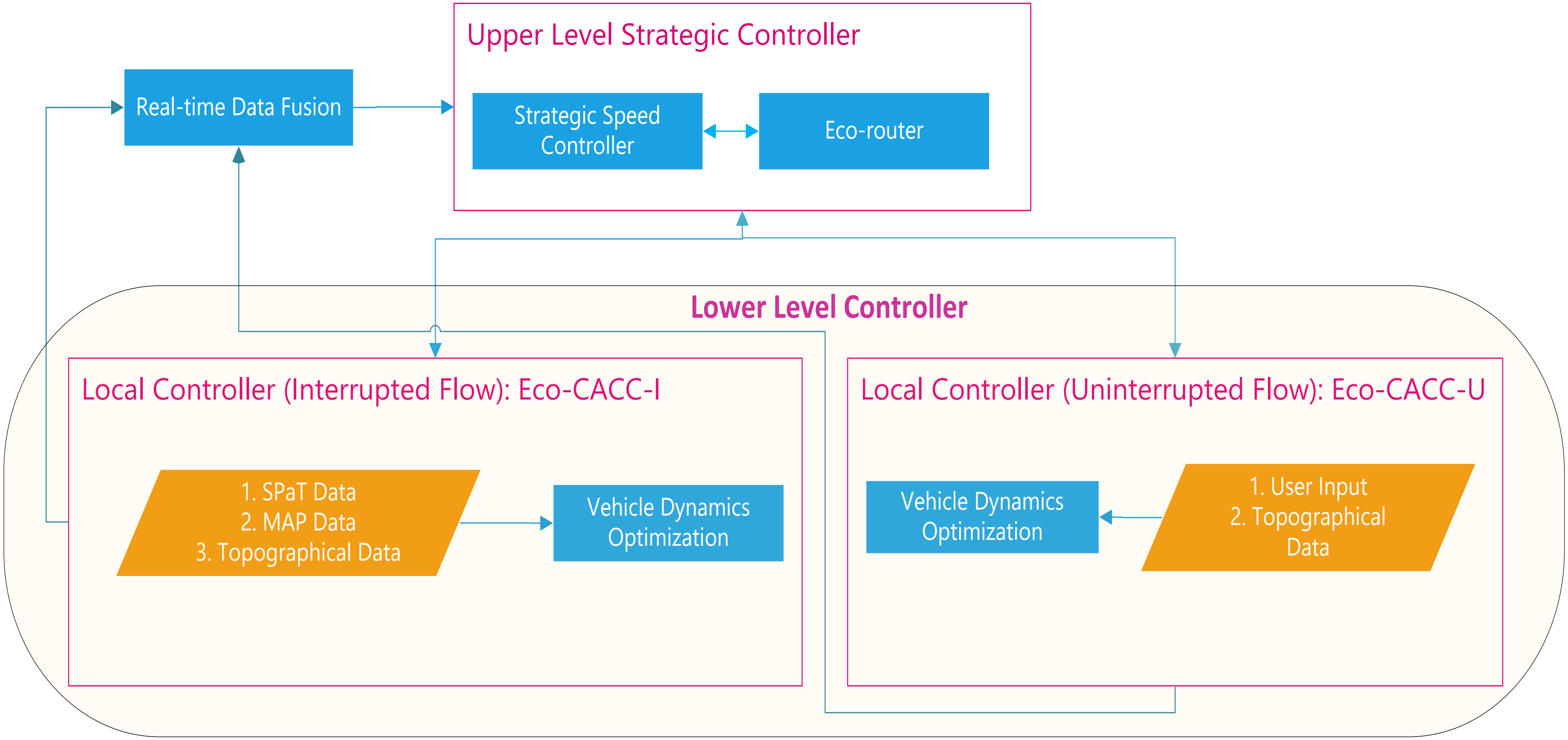
The proposed Eco-CAC system is expected to produce energy/fuel savings of at least 20% in ICEVs, BEVs, PHEVs, and HEVs.

Milestones

Milestones	Planned Completion date	Current Progress – April 2019
Analytical Eco-routing Algorithm Evaluation Complete	June 2019	Developing eco-routing algorithms
Network Monitoring Algorithm Comparison Complete	June 2019	Developing methods to monitor network-wide traffic conditions
Eco-CACC-U Control Strategies Complete	June 2019	Developing Eco-CACC-U controller to regulate platooning vehicles
Eco-CACC-U evaluation complete	June 2019	Developing Eco-CACC-U evaluation plan
Integrated Eco-CAC System Assessment Complete	February 2020	Plan to start July 2019
Simulation Model Assessment Complete	March 2020	Plan to start July 2019
Sensitivity Analysis Complete	June 2020	Plan to start January 2020
Eco-CAC Simulation Prototype Evaluation Complete	June 2020	Plan to start March 2020

Approach Overview

- Approach hinges on connected automated vehicle (CAV) centric control



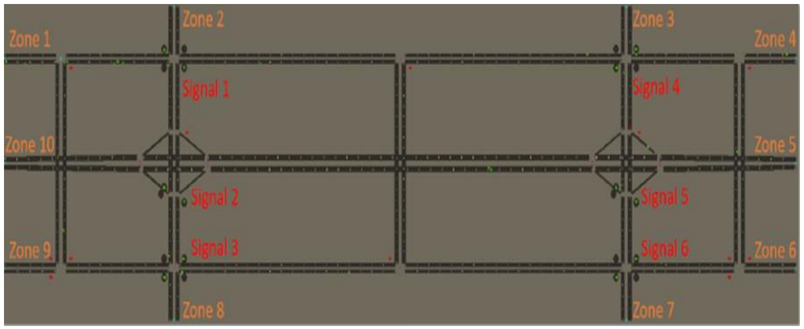
Eco-Router

- Developed a vehicle-agnostic approach to collect transient vehicle data in real-time
  - Entire vehicle trajectory captured using 8 link-specific variables
- Data are sent to the cloud to be fused with existing data and then sent back to CAVs
  - Vehicle-specific link cost computed using the combination of vehicle parameters and the 8 link-specific variables
- Algorithm was implemented in INTEGRATION to generate
  - A dynamic stochastic incremental multi-class user-equilibrium traffic assignment
    - Minimum paths computed using the Dijkstra algorithm

Elbery A. and Rakha H.A. (2019), "City-wide Eco-routing Navigation Considering Vehicular Communication Impacts," Sensors, Volume 19, Issue 2. [DOE-VT-0008209-J01]

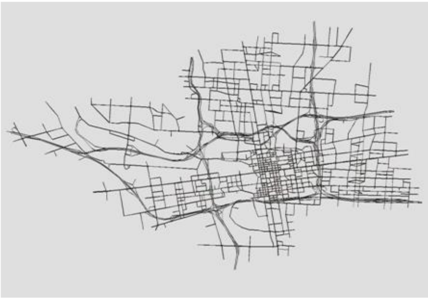
Eco-Router

- Corridor Sample Network Test (QNET)



- Large Network Testing

Cleveland network



Columbus network

Eco-routing results on QNET

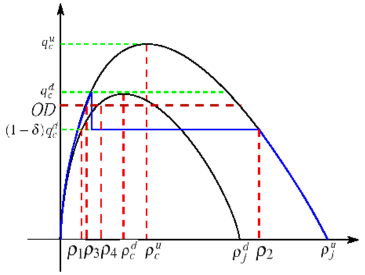
		ICEV (ORNL)			BEV (Nissan Leaf)		
		Eco Routing			Eco Routing		
		0%	50%	100%	0%	50%	100%
Uncongested	Energy(kw)/Fuel(l)	0.34	0.33	0.32	2326	2270	2149
	Energy/Fuel saving		2.7%	5.5%		2.4%	7.6%
	Travel time (s)	151	151	151	151	202	262
	Delay (s)	15.9	15.1	14.8	15.9	31.3	56.2
Congested	Energy(kw)/Fuel(l)	0.35	0.35	0.34	2312	2479	2254
	Energy/Fuel saving		1.2%	3.3%		-7%	2.5%
	Travel time (s)	163	163	169	162	792	1101
	Delay (s)	28.5	27.5	32.6	27.5	436	726

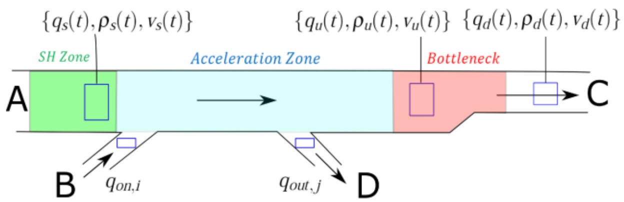
Eco-routing results on Cleveland and Columbus networks

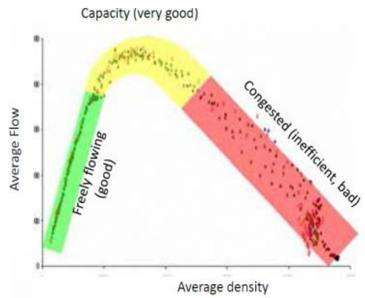
		ICEV (ORNL)			BEV (Nissan Leaf)		
		Eco Routing			Eco Routing		
		0%	50%	100%	0%	50%	100%
Cleveland	Energy(kw)/Fuel(l)	0.57	0.56	0.54	3199	2757	1880
	Energy/Fuel saving		1.9%	4.8%		13.8%	41.2%
	Travel time (s)	315	323	326	315	415	501
	Delay (s)	76.2	81.5	85.1	76.6	156	252
Columbus	Energy(kw)/Fuel(l)	0.67	0.65	0.64	3838	3443	2845
	Energy/Fuel saving		2.27%	5.01%		10.3%	25.9%
	Travel time (s)	314	323	333	314	390	532
	Delay (s)	65.1	71.2	77.7	64.9	104.8	229.9

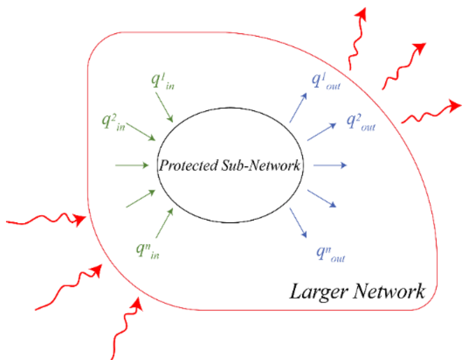
Strategic Speed Controller

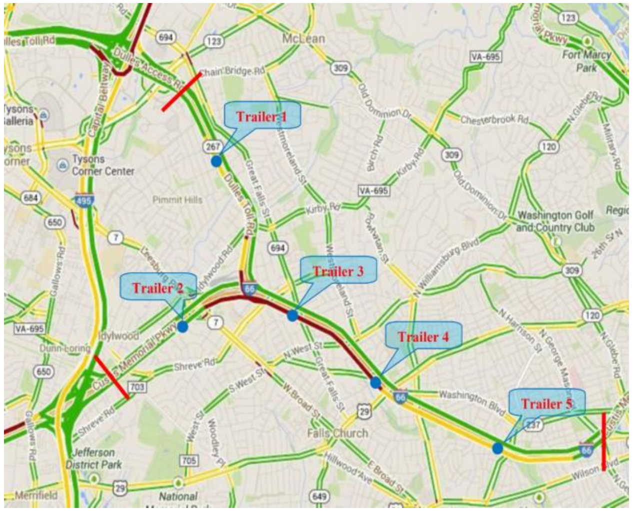
- Builds on a previously developed for single bottlenecks
  - An MPR=10% is sufficient to work successfully
    - a CAV flow of 400 veh/h (167 veh/h/lane)
- Developed a variable structure feedback controller
  - CAV-based algorithm regulates the flow of traffic approaching congested regions within a transportation system



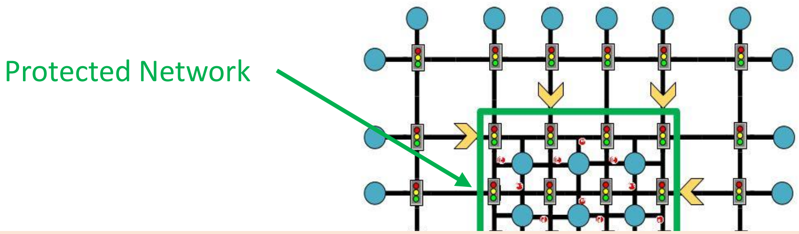








Strategic Speed Controller



Sensitivity of sliding mode controller with respect to the no-control case for various values of controller parameters (**λ**, **η**).

		TT (s)	Delay (s)	Fuel (L)	Speed (km/h)
No control Case		674.29	267.12	0.43	14.67
250.000	350.000	-2.09	0.69	-16.88	2.20
70.000	130.000	-10.09	-16.89	-21.63	8.79
50.000	0.100	-8.93	-16.64	-21.36	7.65
120.000	0.895	-12.25	-14.84	-20.63	12.28
20.000	120.000	-12.56	-18.67	-22.03	11.84
0.580	10.000	-13.29	-20.50	-22.68	12.45

Du J. and Rakha H.A. (2019), “Constructing a Network Fundamental Diagram: A Synthetic Origin-Destination Approach,” Transportation Research Board (TRB) 98th Annual Meeting, Washington DC, Jan. 13-17, Paper: 19-00044. [DOE-VT-0008209-C02]

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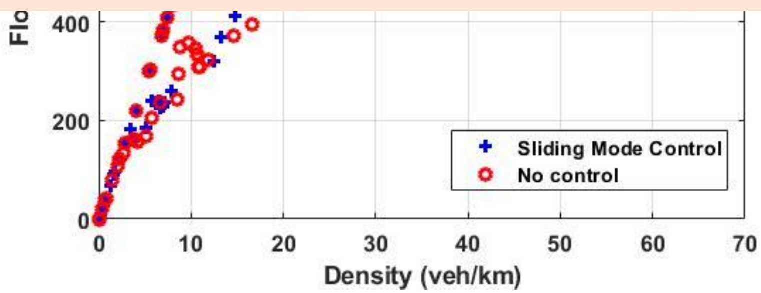
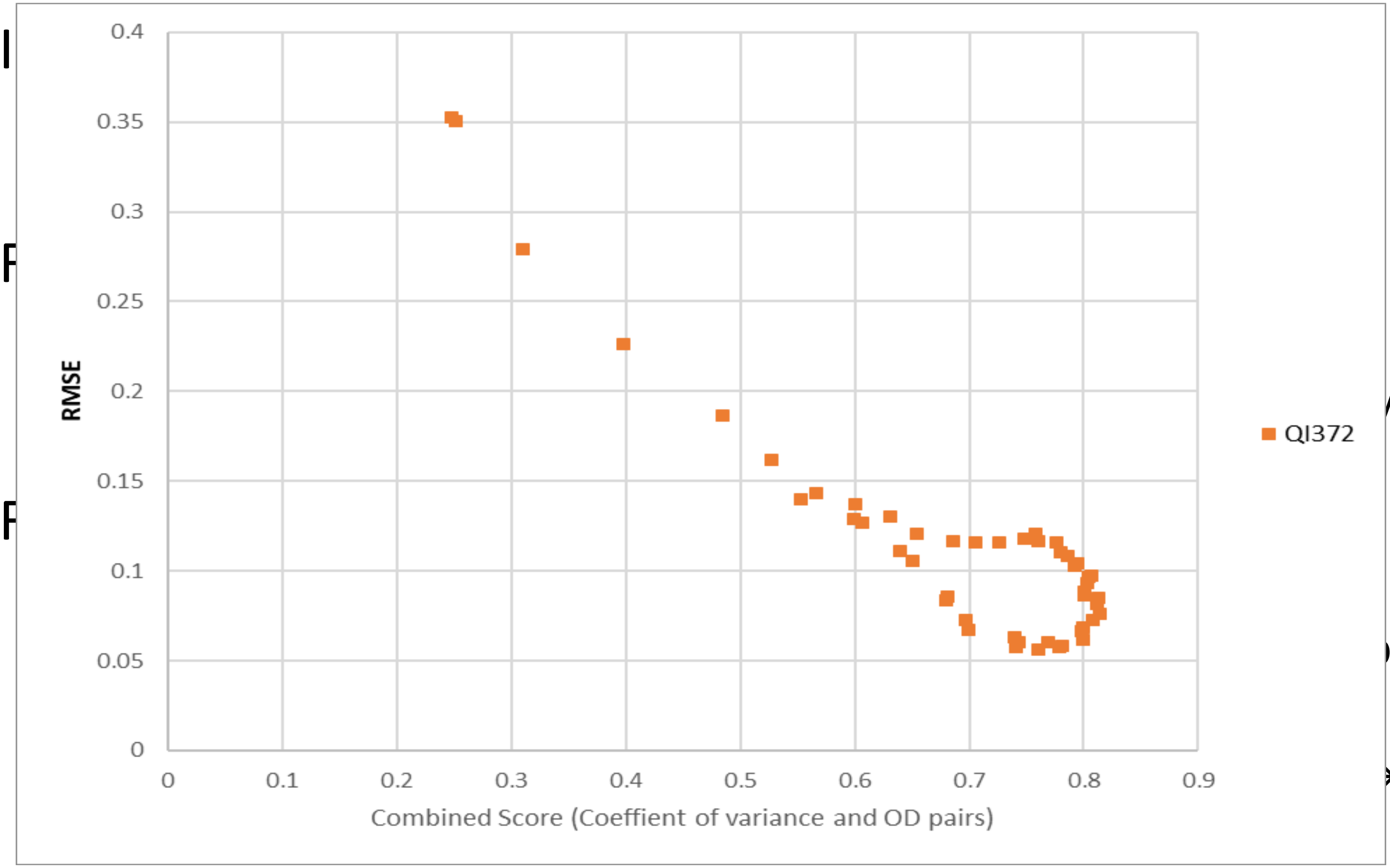


Strategic Speed Controller

- Controller performance depends on the accuracy of the constructed NFD from CV and stationary sensor data
  - I
  - F
  - F



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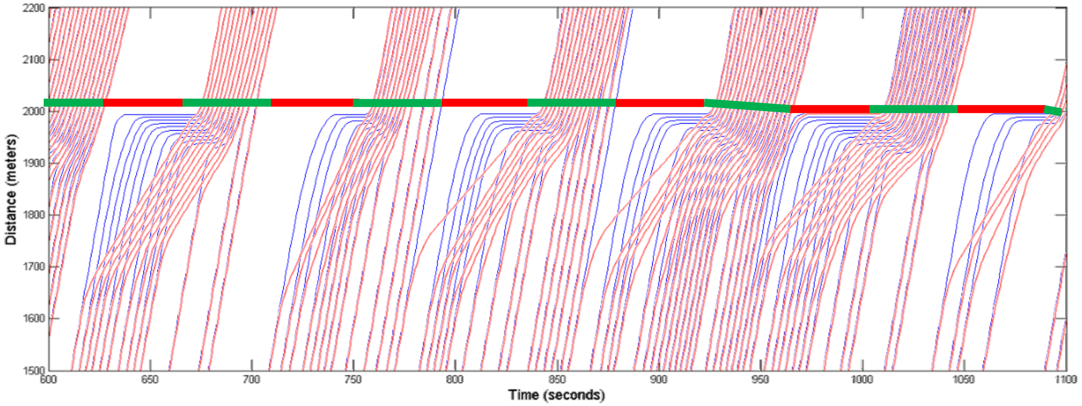
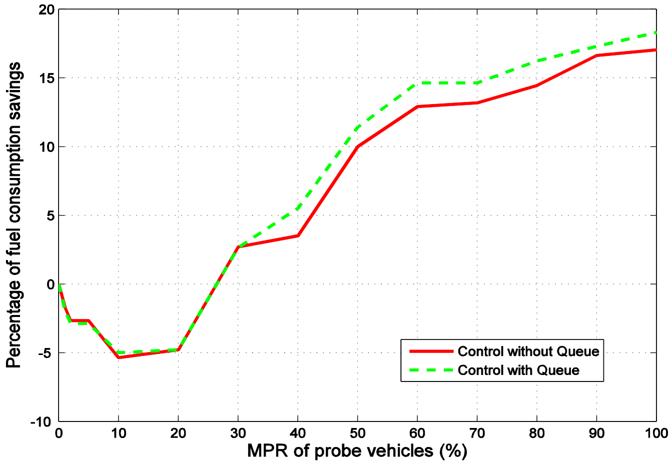
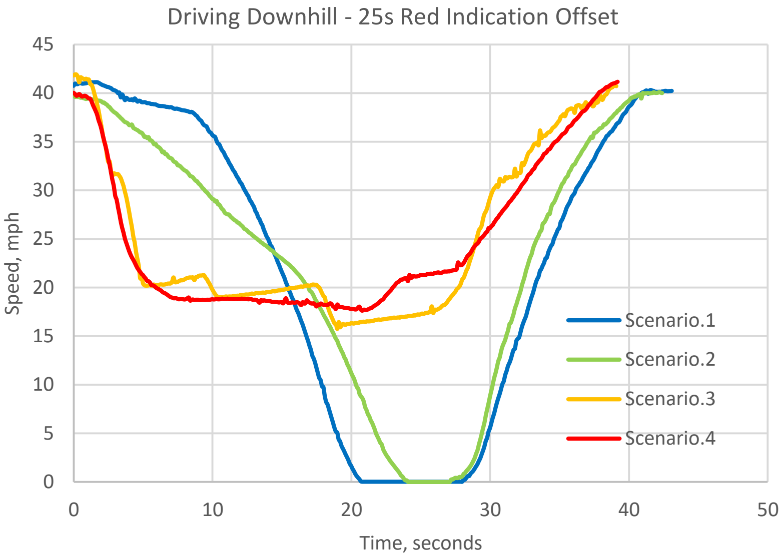
Eco-CACC-I Controller



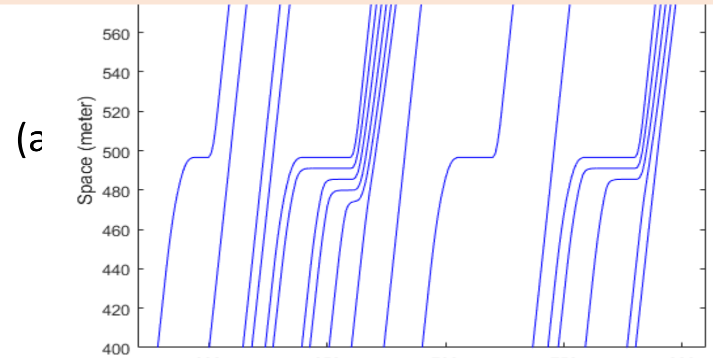


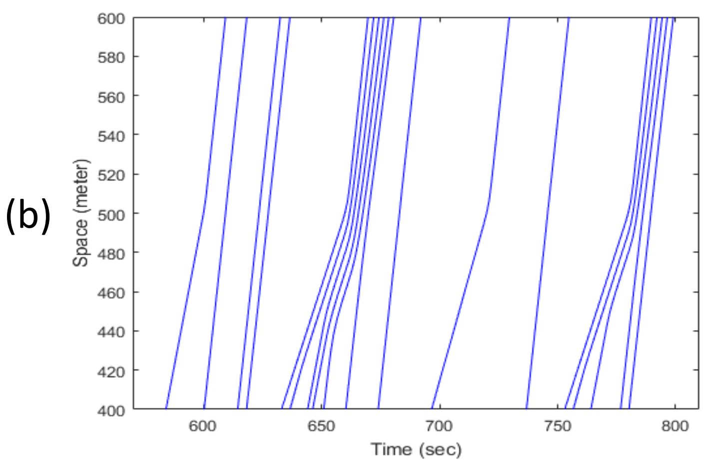


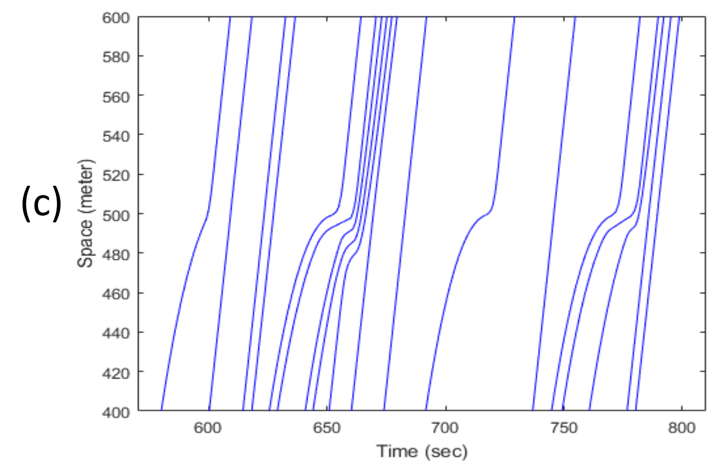
Eco-CACC-I Controller

Chen H. and Rakha H.A. (2019), “Developing a Traffic Signal Eco-Cooperative Adaptive Cruise Control System for Battery Electric Vehicles,” Transportation Research Board (TRB) 98th Annual Meeting, Washington DC, Jan. 13-17, Paper: 19-00572. [DOE-VT-0008209-C01]

	BEV	ICEV
Uphill	Max. decel	Mid-range decel
Downhill	Min. decel	Max. decel



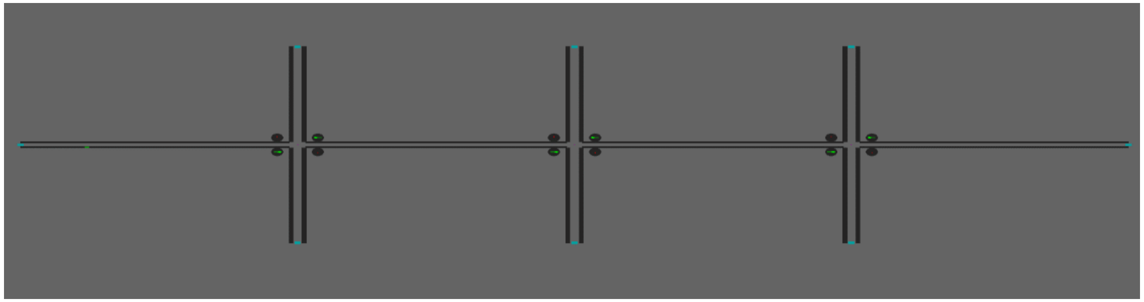




Vehicle trajectories on downhill roadway for (a) uninformed drive; (b) ICEV Eco-CACC-I; (c) BEV Eco-CACC-I.

Eco-CACC-I Controller

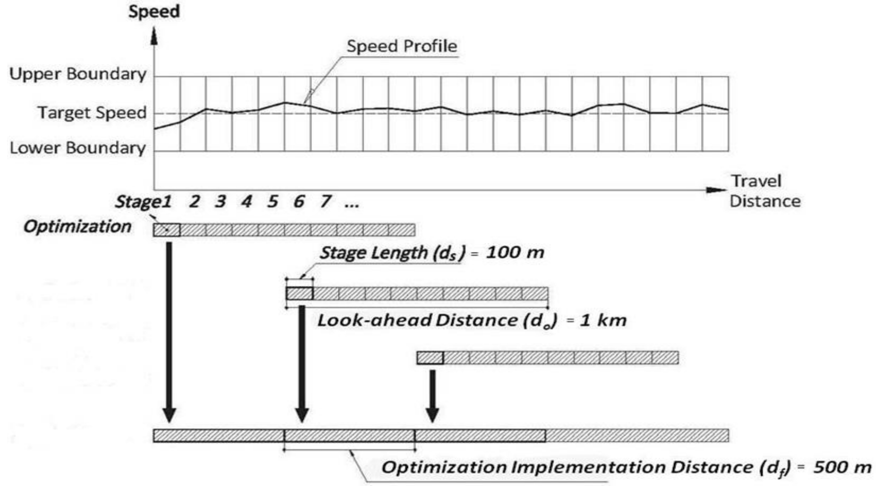
- Implemented & tested Eco-CACC-I controller in INTEGRATION

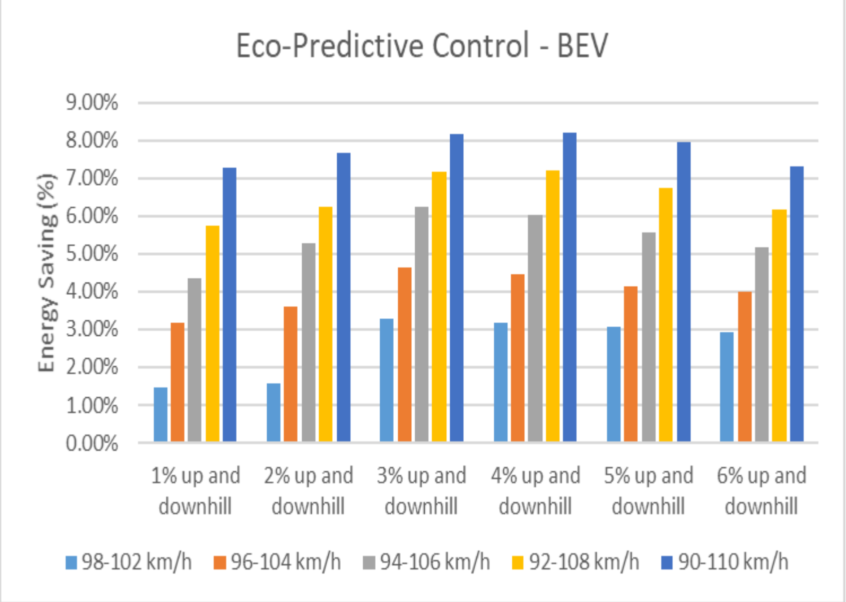


OD Demand	Test Scenario	Average Energy Consumption (KW)	Average Total Delay (sec)	Average Vehicle Stops
25% Demand	Without Eco-CACC-I	942.63	31.65	1.87
	With Eco-CACC-I	854.93	30.41	1.44
	Reduction	9.3%	3.9%	23.0%
50% Demand	Without Eco-CACC-I	880.92	38.41	1.92
	With Eco-CACC-I	815.6	36.98	1.53
	Reduction	7.4%	3.7%	20.3%
75% Demand	Without Eco-CACC-I	851.13	55.67	2.12
	With Eco-CACC-I	810.97	50.42	1.69
	Reduction	4.7%	9.4%	20.3%
100% Demand	Without Eco-CACC-I	850.84	118.45	2.74
	With Eco-CACC-I	832.95	112.43	1.98
	Reduction	2.1%	5.1%	27.7%

Eco-CACC-U Controller

- BEV Lead Vehicle Control:
  - The lead vehicle control computes optimum speed and acceleration levels within a preset speed window to minimize the energy consumption considering instantaneous electricity used and regenerative energy in response to changes in roadway grades.





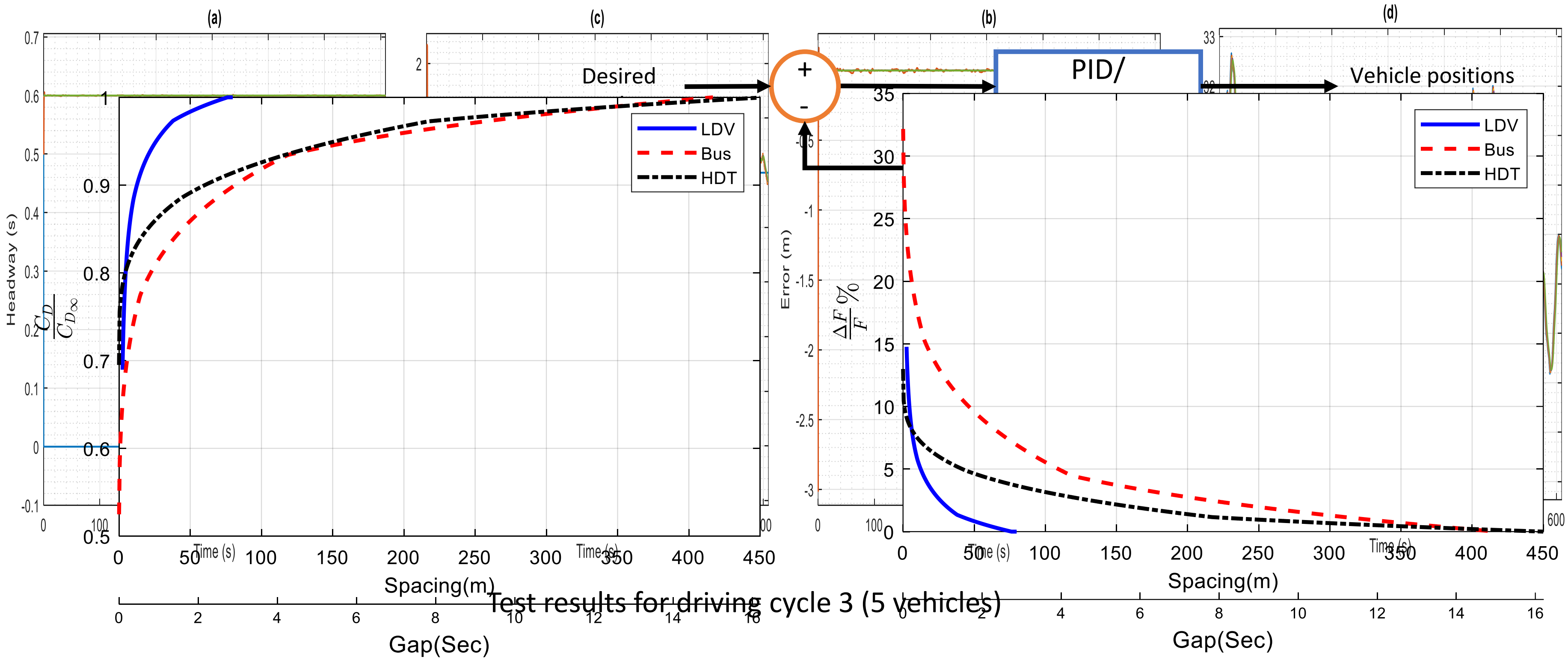
Energy saving of BEV eco-predictive control

BEV Eco-predictive control results on section of I-81

	I-81 - Southbound			I-81 – Northbound		
Speed range	Energy (kWh)	Energy Saving	Range (mi)	Energy (kWh)	Energy Saving	Range (mi)
104 km/h (base case)	3.58	0.00%	75.48	1.55	0.00%	173.95
102 – 106 km/h	3.52	-1.56%	76.68	1.51	-2.80%	178.96
100 – 108 km/h	3.48	-2.76%	77.62	1.48	-4.97%	183.04
98 – 110 km/h	3.44	-3.94%	78.57	1.44	-7.08%	187.21
96 – 112 km/h	3.40	-5.08%	79.52	1.41	-9.16%	191.49
94 – 114 km/h	3.36	-6.19%	80.46	1.38	-11.16%	195.81

Eco-CACC-U Controller

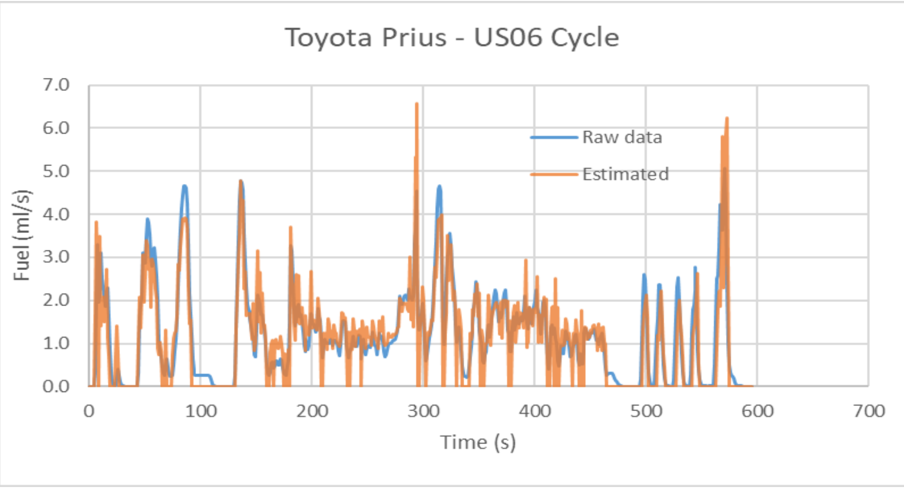
- We developed two controllers that allow vehicles to platoon
  - PID Controller
  - Simple feedback controller

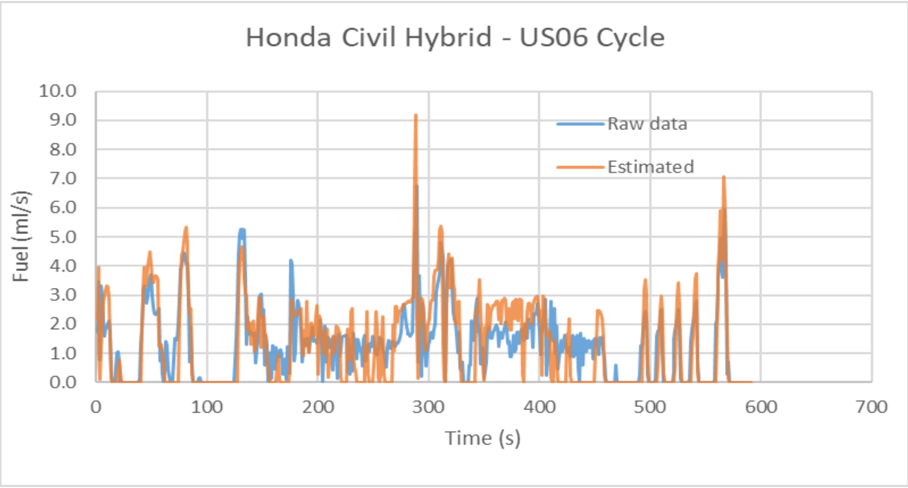


Test results for driving cycle 3 (5 vehicles)

HEV Model Development

- Developed a new power-based microscopic Hybrid Electric Vehicle (HEV) fuel consumption model using 2010 Toyota Prius data
- $FC(t) = \begin{cases} a + bv(t) + cP(t) + dP(t)^2 & \text{for } (P > 0 \text{ and } v \geq 32\ km/h) \text{ or } (v < 32\ km/h \text{ and } P \geq 10\ kW) \\ Fuel_{EV\_mode} & \text{for } P \leq 0 \text{ or } (v < 32\ km/h \text{ and } P < 10\ kW) \end{cases}$
- The proposed model utilizes instantaneous vehicle speed, acceleration, and roadway grade as input variables. The model estimates vehicle fuel consumption rates consistent with empirical data with an average error of 2.1%.
- The model was then generalized for other HEV vehicles using a scale factor that is computed as the ratio of the vehicle EPA combined rating. The model estimates the vehicle fuel consumption with an average error up to 5% for different HEVs.
  - The measured fuel consumption for the 2015 Honda Accord Hybrid, 2013 VW Jetta Hybrid, 2013 Honda Civic Hybrid, and 2010 Ford Fusion Hybrid were 1.397, 1.625, 1.583, and 1.924 liters and the estimated fuel consumption was 1.469, 1.564, 1.604, and 1.845 liters, respectively. Consequently, the error were 5%, 4%, 1%, and 4%,





Responses to Reviewer Comments

- Re: Up to 10% error in HEV energy model, we updated the HEV energy model.
  - Average error of 2.1% for the Toyota Prius and up to 5% for other HEVs.
- Re: Unrealistic driving behavior of Eco-CACC-I operation, we updated the ECO-CACC-I algorithm
  - As demonstrated Slide 12, the Eco-CACC-I test vehicles show realistic driving behaviors.
- Re: Validating the model for real world driving conditions for Eco-CACC-U operation, we tested the algorithm for realistic driving conditions in Matlab and will implement and test them in the INTEGRATION software.
- Re: Travel time increases for Eco-routing, we are implementing a multi-objective objective function to compute a compromise solution.

Collaborations and Coordination

- No collaboration partners within the DOE funding given that the team consists of a single institution.
- Collaboration with Morgan State University (MSU) as part of the University Mobility and Equity Center (UMEC)
  - Tested our Eco-CACC-I system on test subjects in a driving simulator
- Working with ERL, TTS and VDOT to implement and field test the developed Eco-CACC-I system
  - Working on dealing with actuated traffic signal SPaT data

Remaining Challenges and Barriers

- Combining re-routing with gating did not improve the overall results compared to gating alone
- Vehicle-centric speed control (gating) is not as effective as signal control on signalized roadways
  - Use strategic speed control on freeways and CV-based traffic signal control at signalized intersections
- We found the BEV eco-routing model reduced the vehicle energy consumption significantly but also increased travel times significantly
  - We are developing multi-objective objective functions that ensure some compromise solution using user-defined weights

Proposed Future Work

- Ongoing work – FY19
  - Eco-Routing System Development
  - Strategic Control Algorithm Development
  - Eco-CACC-I Development
  - Eco-CACC-U Development
- Future work - FY19 and FY20
  - Integrated Eco-CAC System Assessment (July 2019)
  - Simulation Model Assessment (July 2019)
  - Sensitivity Analysis (December 2019)
  - Eco-CAC simulation prototype evaluation (April 2019)
- Any proposed future work is subject to change based on funding levels.

Summary

- Budget Period 1 tasks are on track for evaluation during 2nd quarter of 2019.

Tasks	Percentage completion	Key Technical Results
Eco-routing model development	80%	• Developed Eco-routing models for ICEVs and BEVs • Developed HEV energy model
Network monitoring algorithm development	85%	• Testing LA downtown network • MFD to monitor the state of a transportation network
Eco-CACC-I controller development	90%	• Developed Eco-CACC-I control model for BEVs
Eco-CACC-U controller development	80%	• Developing car-following module for platooning

Technical Backup Slides

Publications

- Chen H. and Rakha H.A. (2019), “Developing a Traffic Signal Eco-Cooperative Adaptive Cruise Control System for Battery Electric Vehicles,” Transportation Research Board (TRB) 98th Annual Meeting, Washington DC, Jan. 13-17, Paper: 19-00572. [DOE-VT-0008209-C01]
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